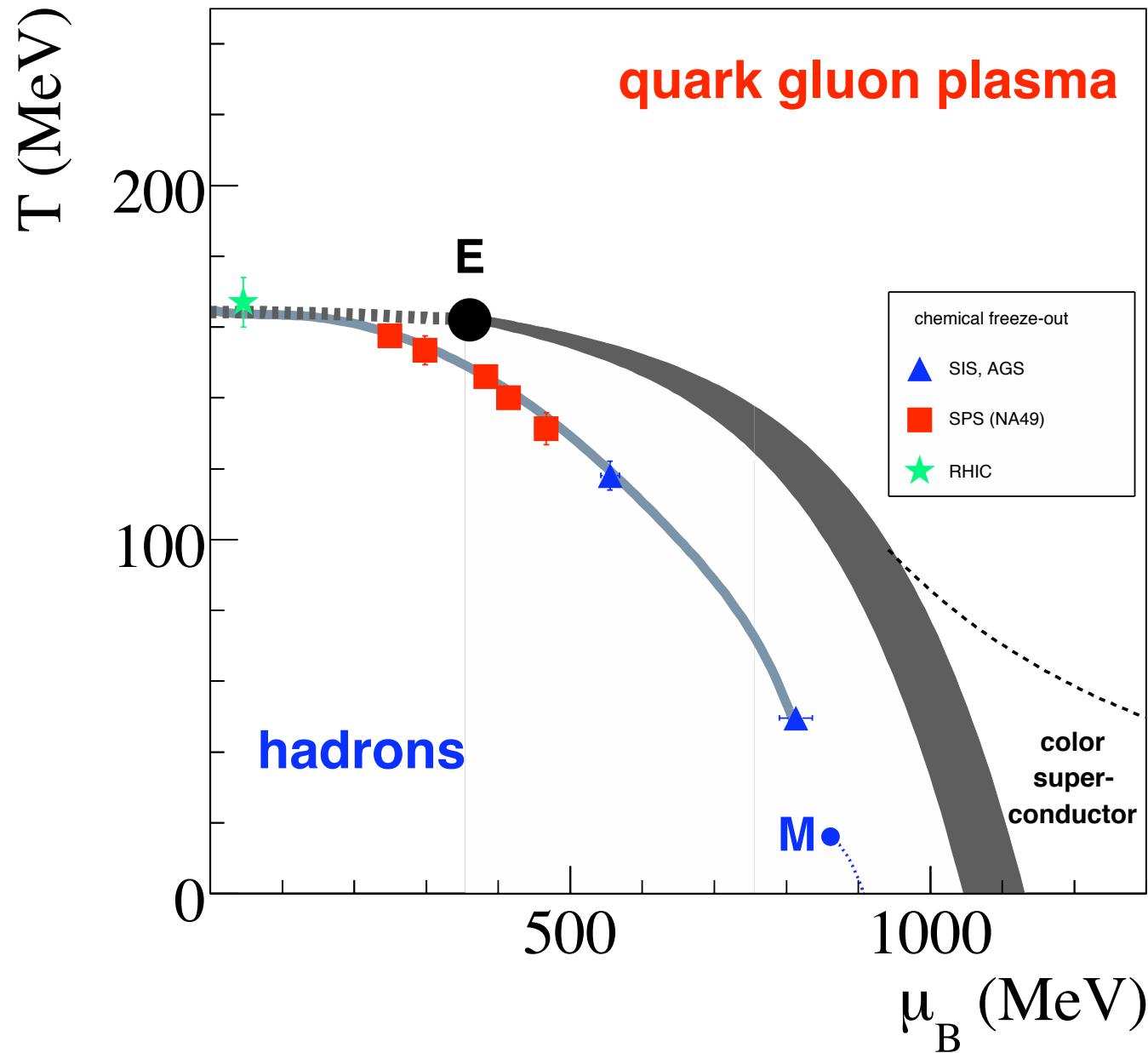


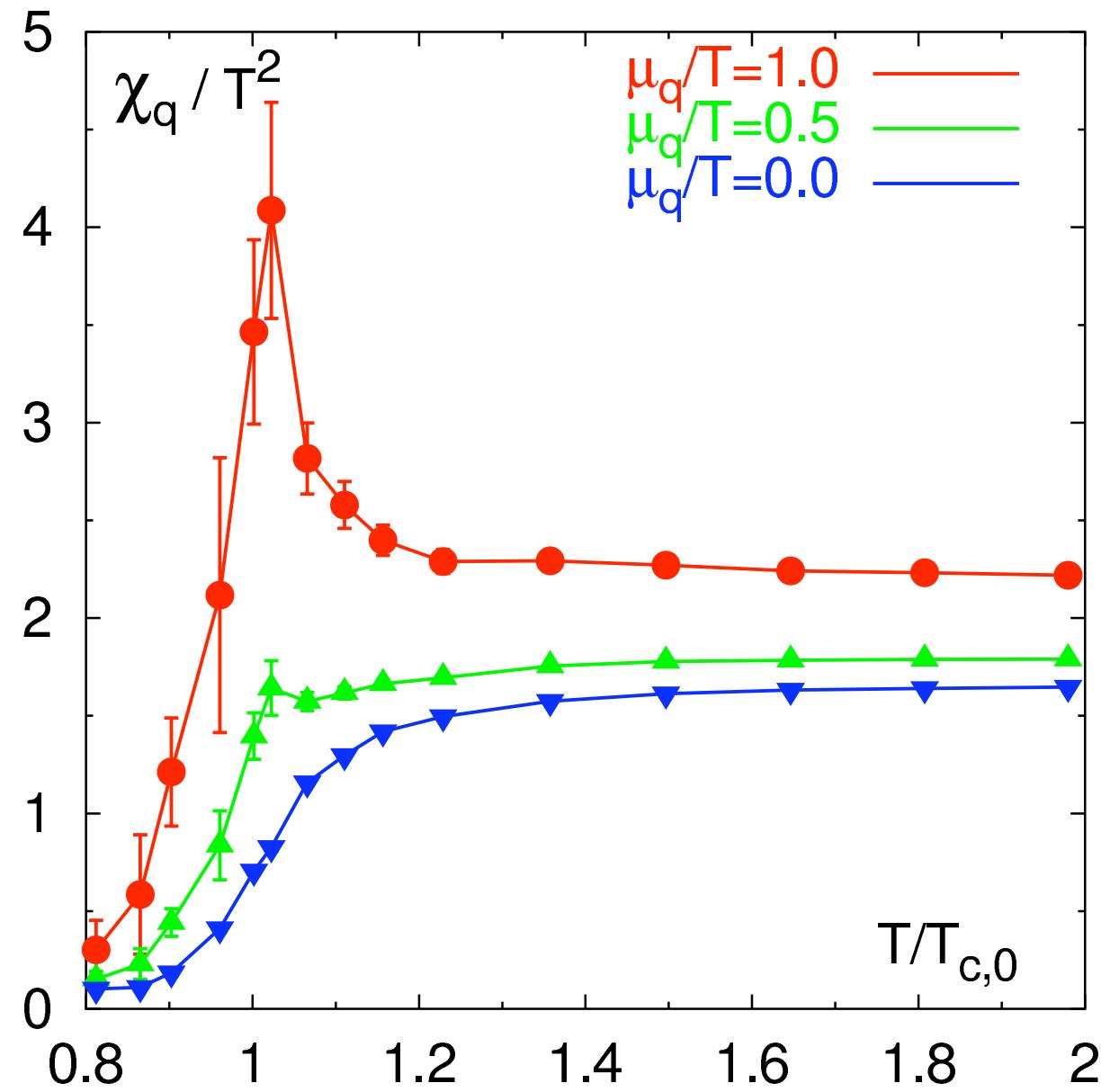
**5<sup>th</sup> International Workshop on  
Critical Point and Onset of Deconfinement  
BNL - June 8, 2009**

# The QCD phase diagram: Expectations and Challenges

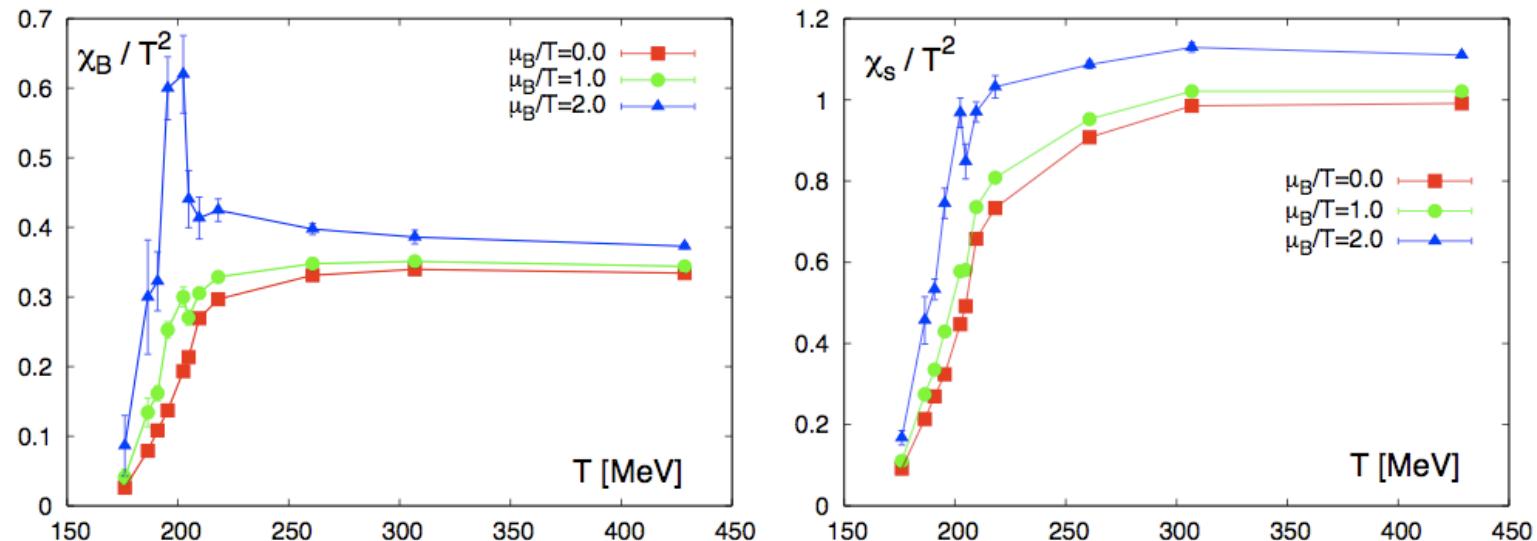
Reinhard Stock, Goethe University Frankfurt

# I) History - Intuition



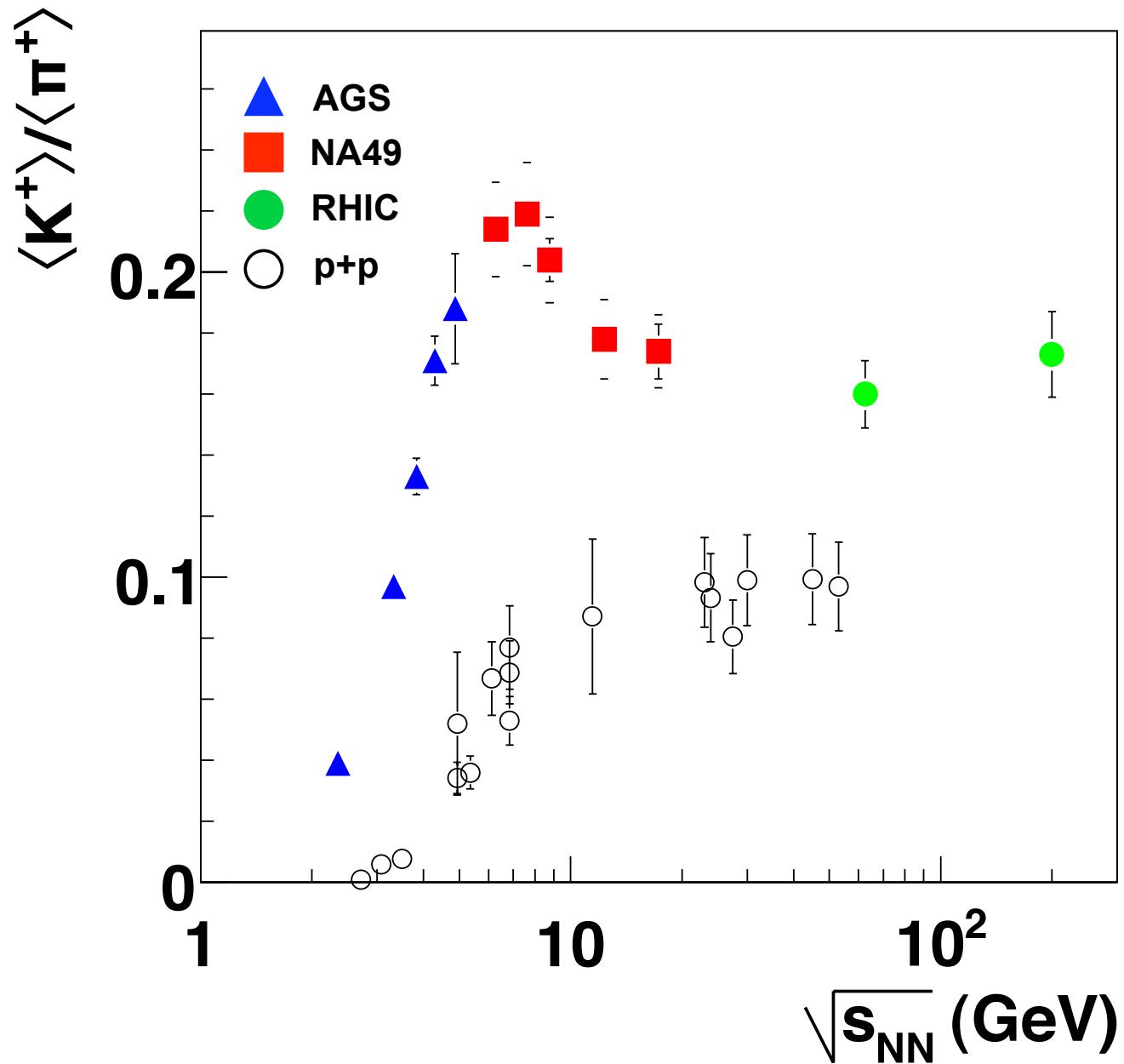


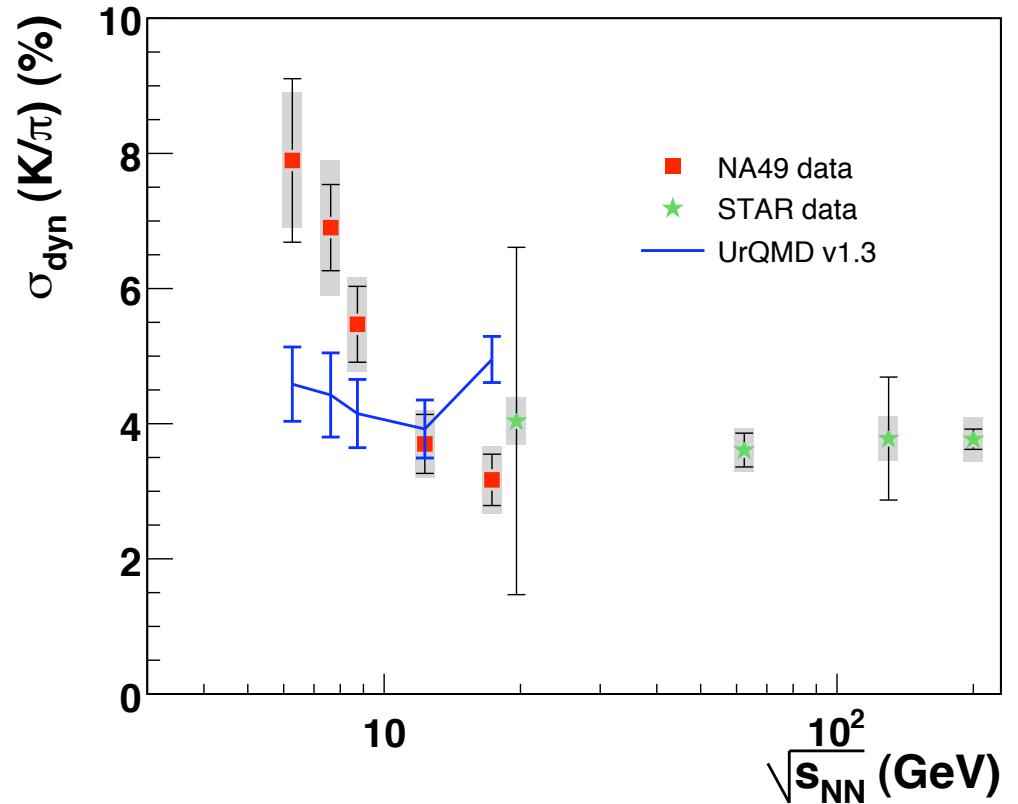
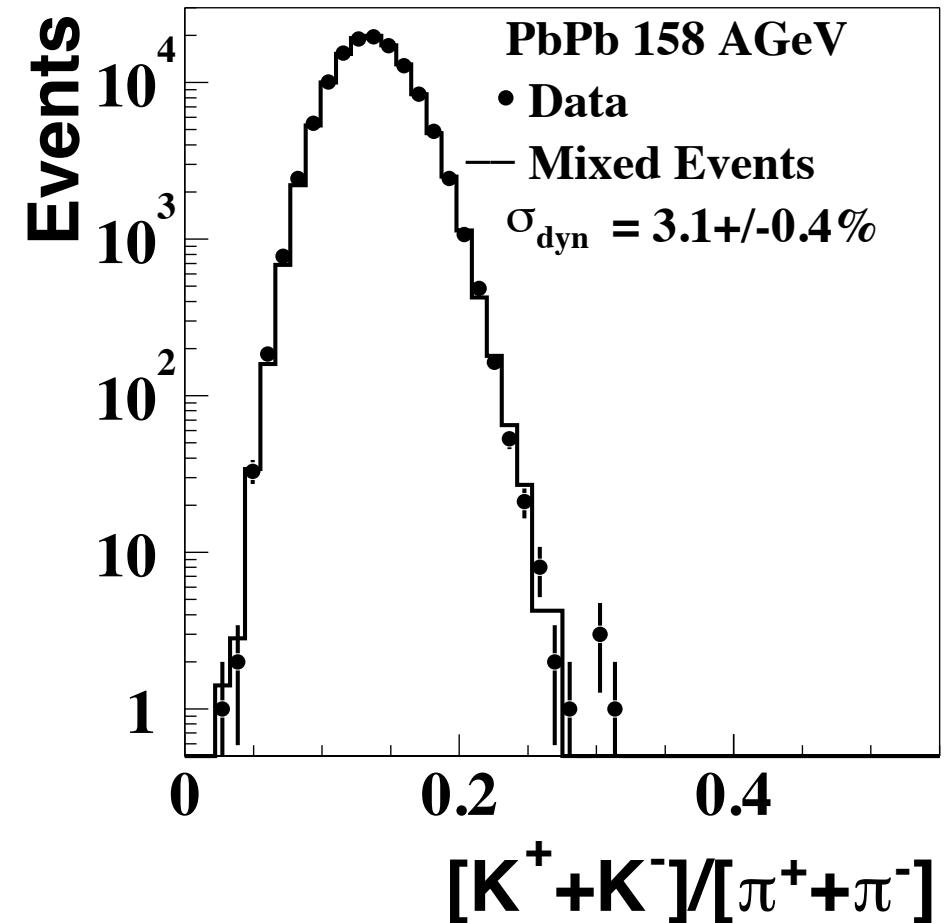
- Lattice calculations show change in quark number susceptibilities



F. Karsch, PoS (CPOD07) 026 and PoS (Lattice 2007) 015

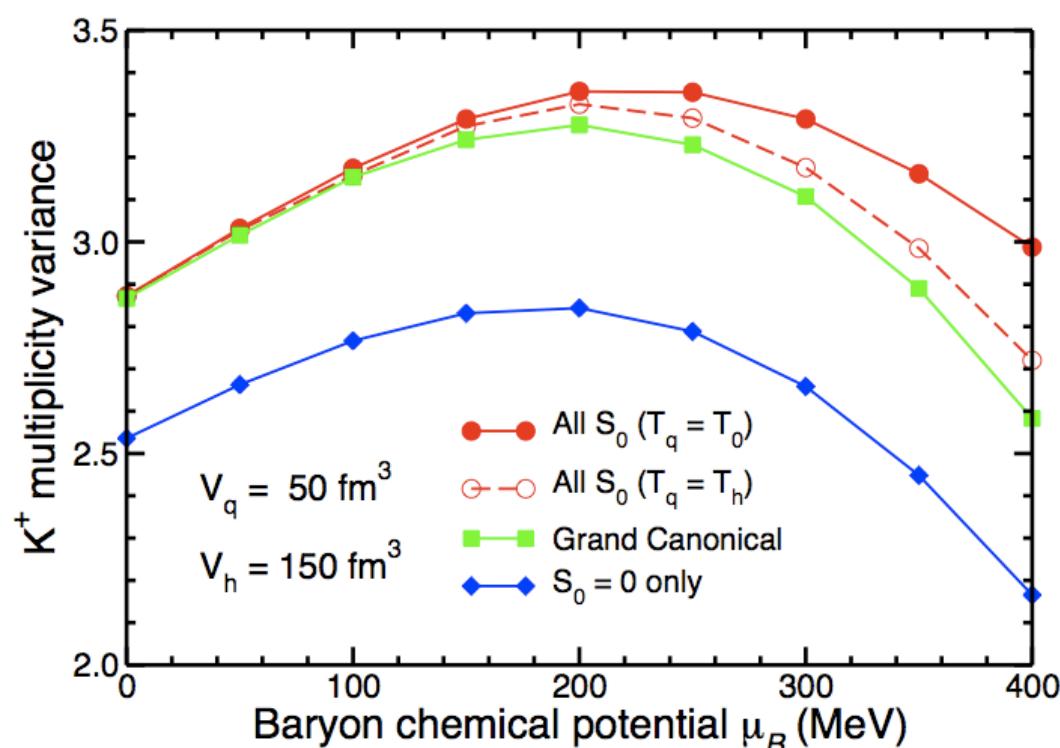
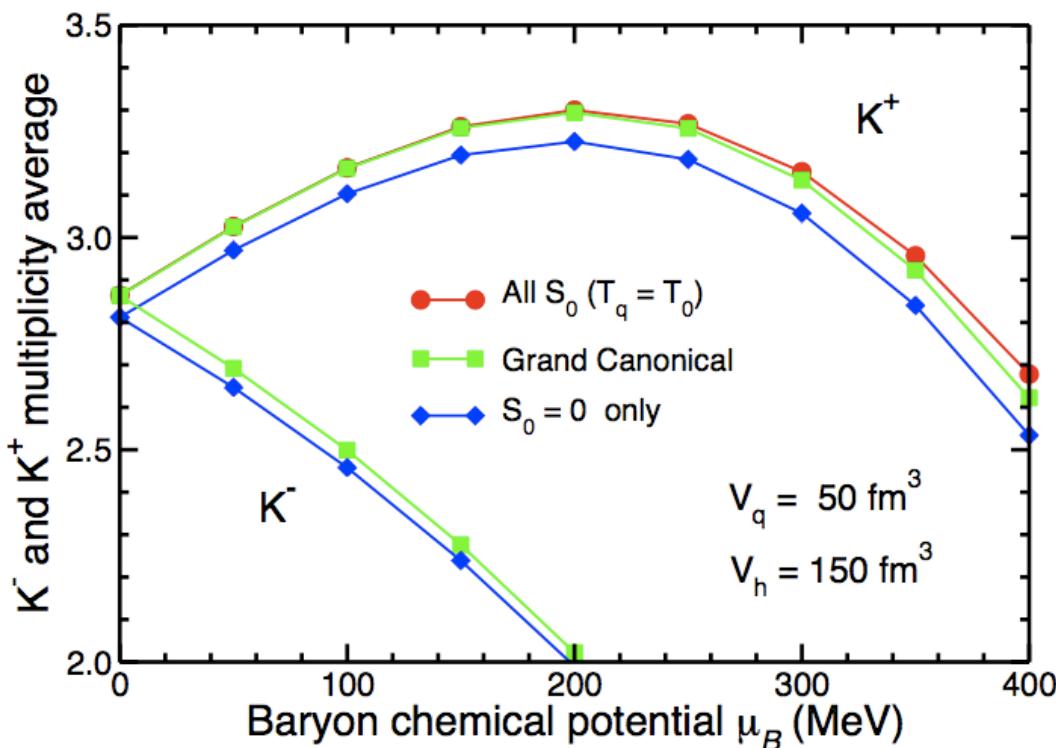
- Direct connection to number fluctuations  $\chi \sim \langle N^2 \rangle$
- Step seen for light and strange quarks
- Smooth transition at  $\mu_B = 0$
- Light quark number susceptibility diverges at the critical point





NA49, Phys. Rev. Lett. 86, 1965 (2001)

# Spinodal decomposition



# Consequences for the phase diagram:

## C. Schmidt, QM08

## the radius of convergence

- the radius of convergence can be estimated by the Taylor coefficients of the pressure:

$$\rho = \lim_{n \rightarrow \infty} \rho_n$$

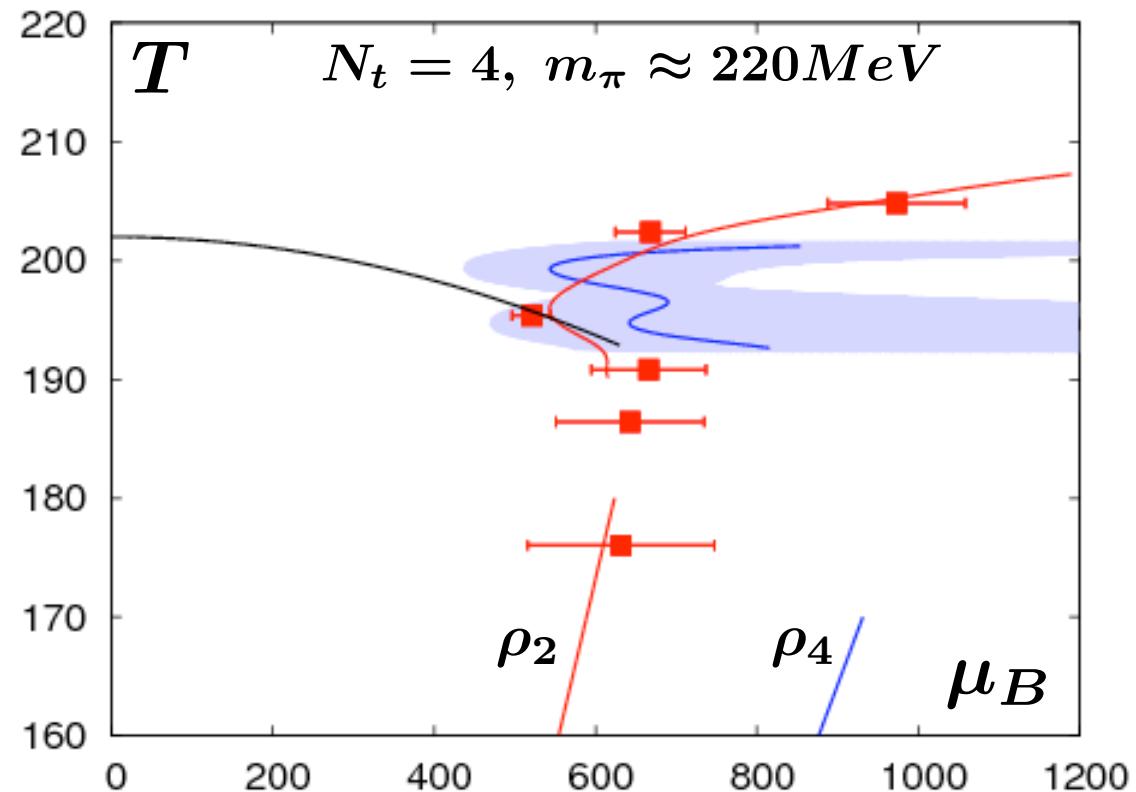
with

$$\rho_n = \sqrt{\frac{c_n^B}{c_{n+2}^B}}$$

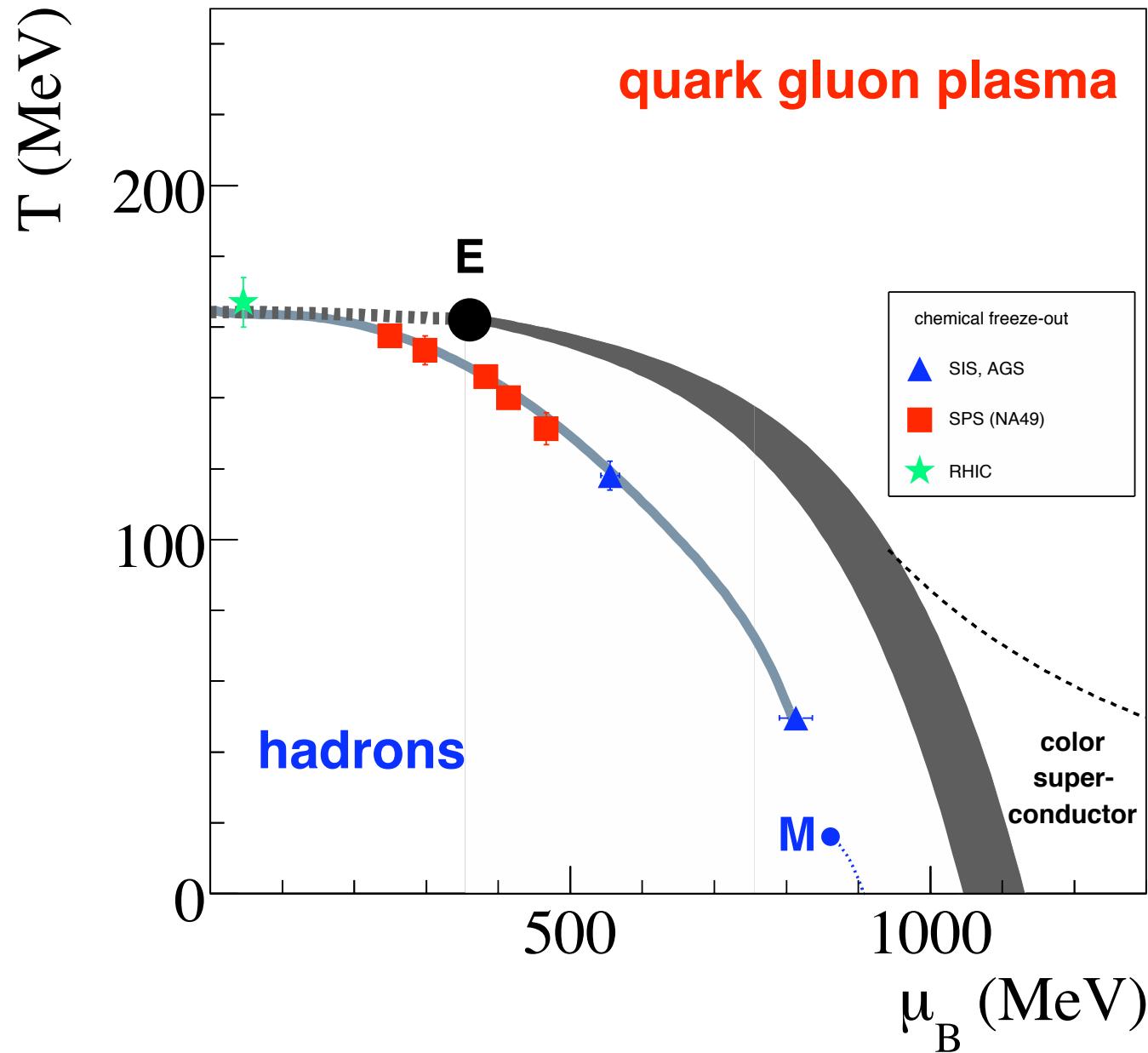
- for  $T > T_c$ ,  $\rho_n \rightarrow \infty$
- for  $T < T_c$ ,  $\rho_n$  is bound by the transition line

- non monotonic behavior of the convergence radius

→ **first hint for a critical region ?**



- higher order approximations are needed to locate the critical point

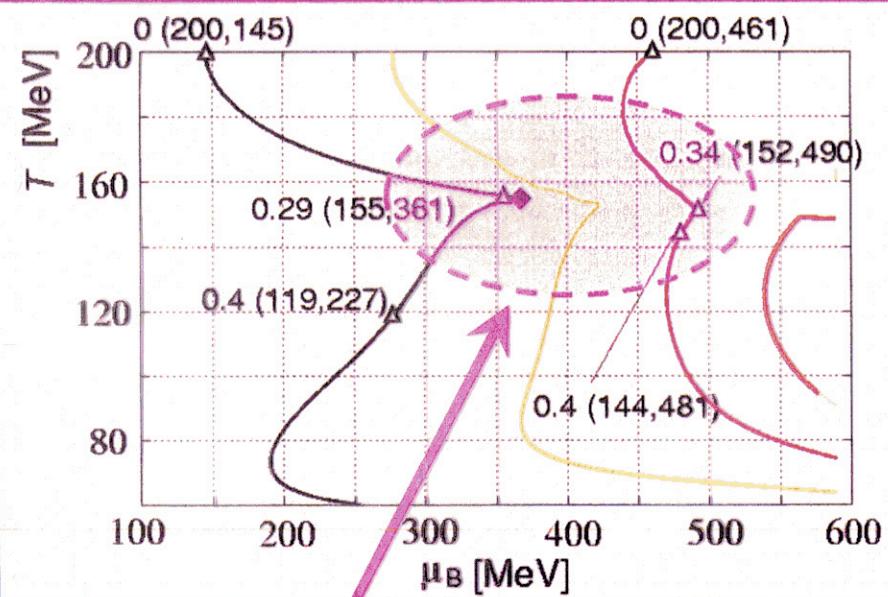


## 2) Recent Developments

### 2.1) Critical Point Focussing Effect

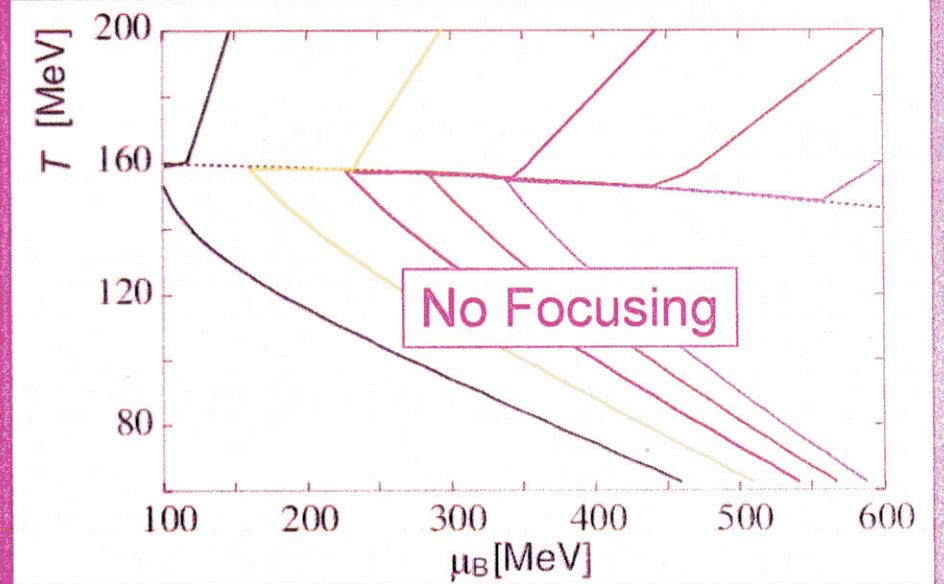
# With Large Critical Region

with CEP



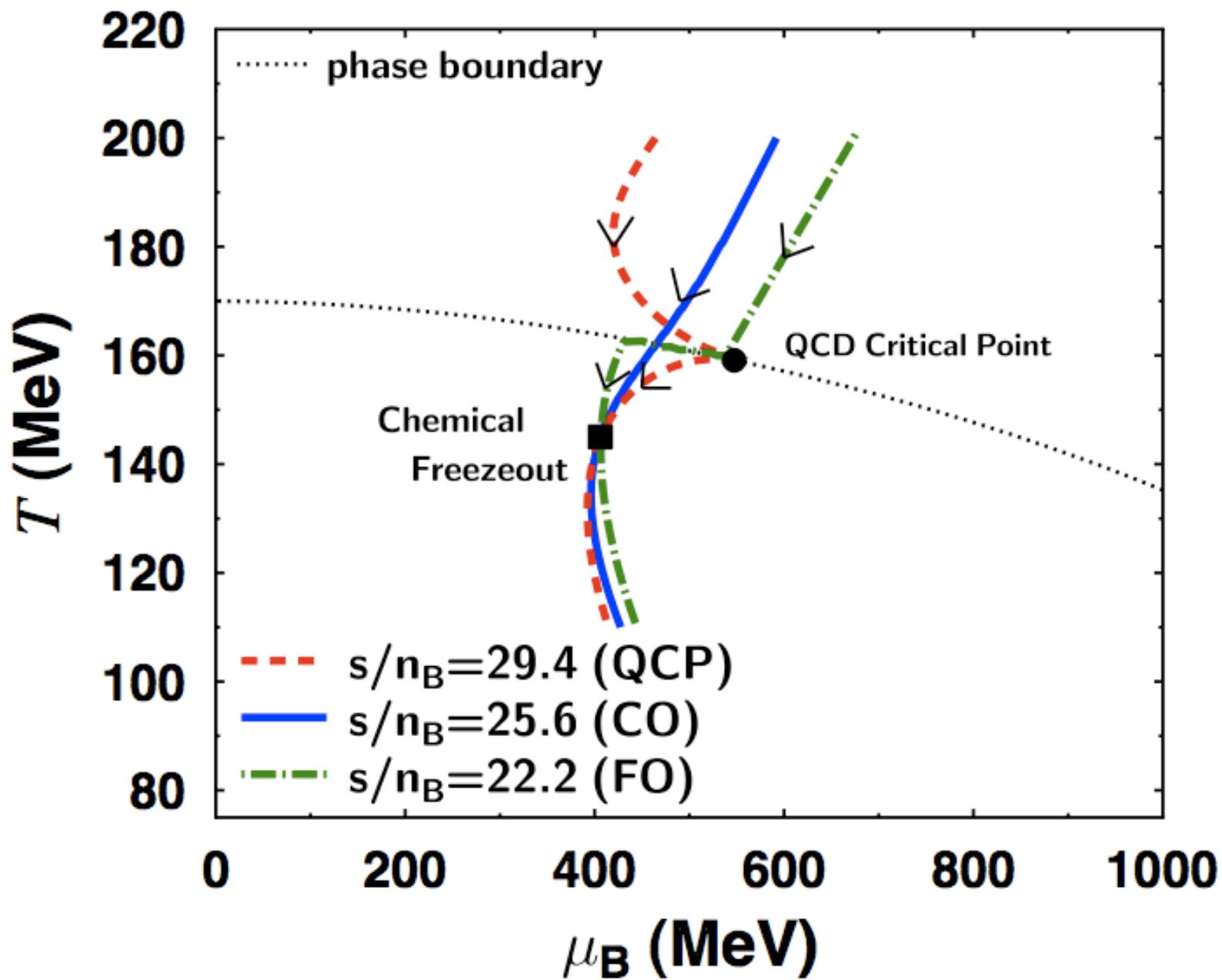
Focusing of Isentropic Trajectories

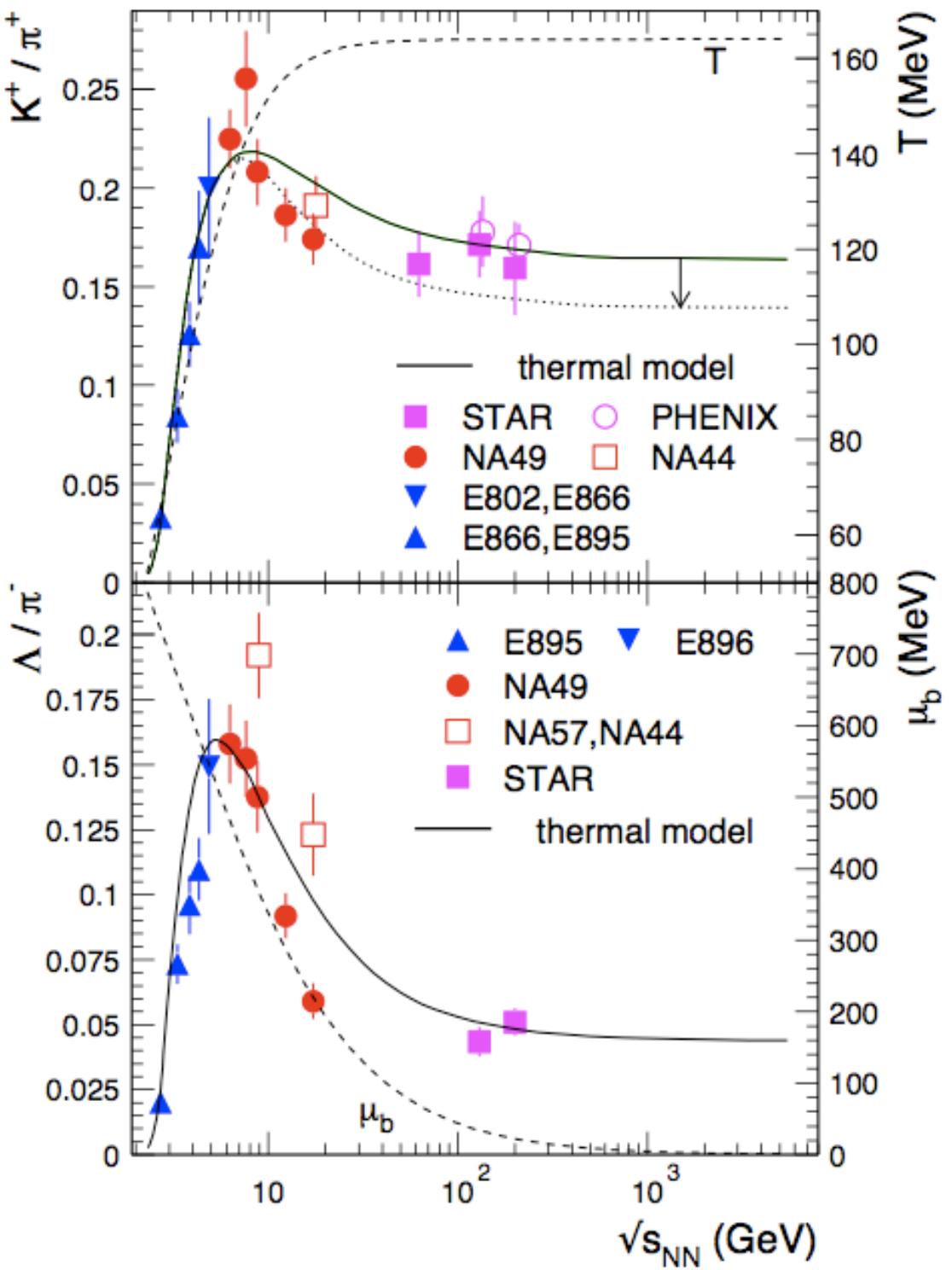
without CEP (EOS in usual hydro calculation)



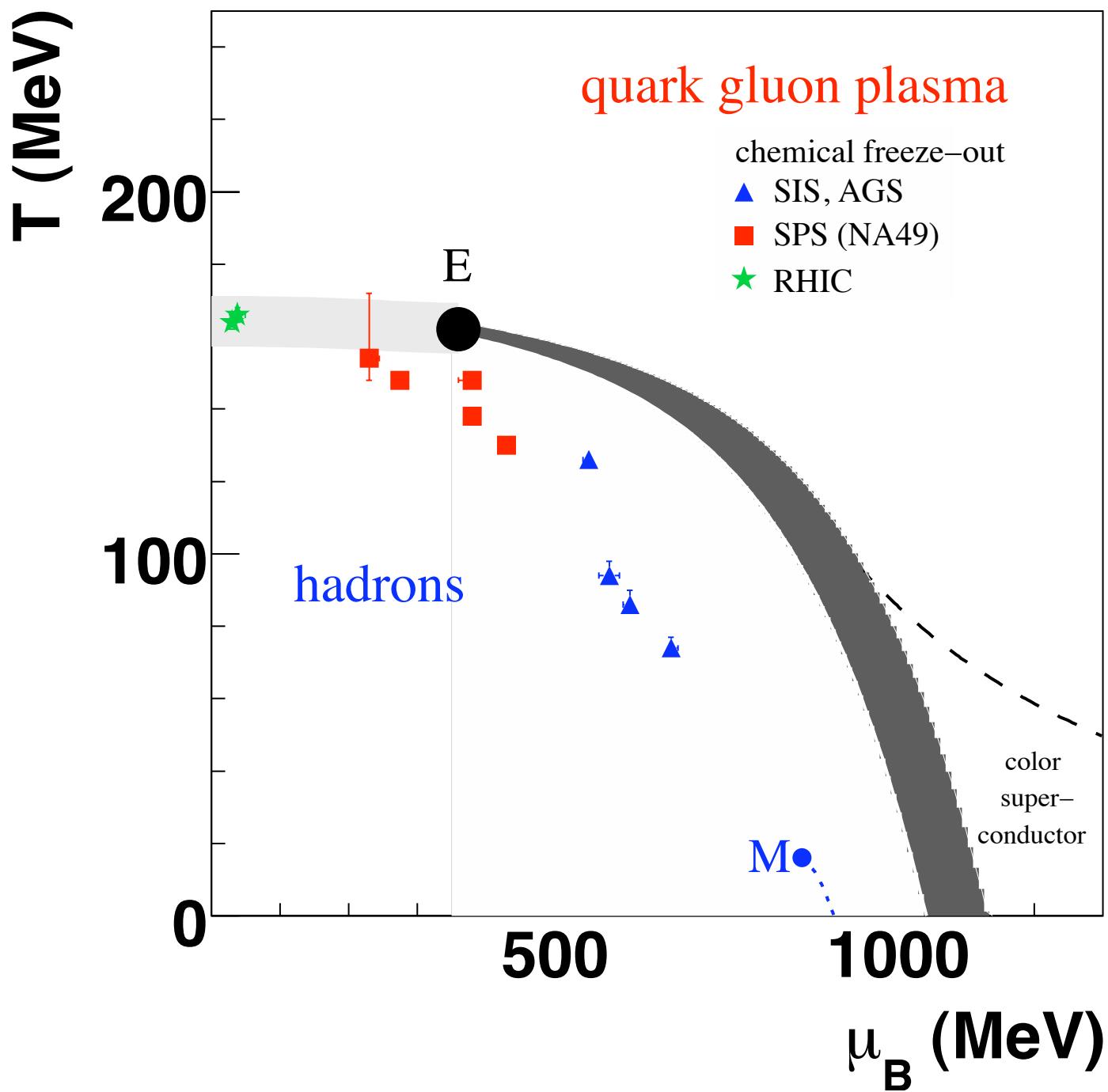
Excluded Volume Approximation  
+ Bag Model EOS

used in most hydro calculations

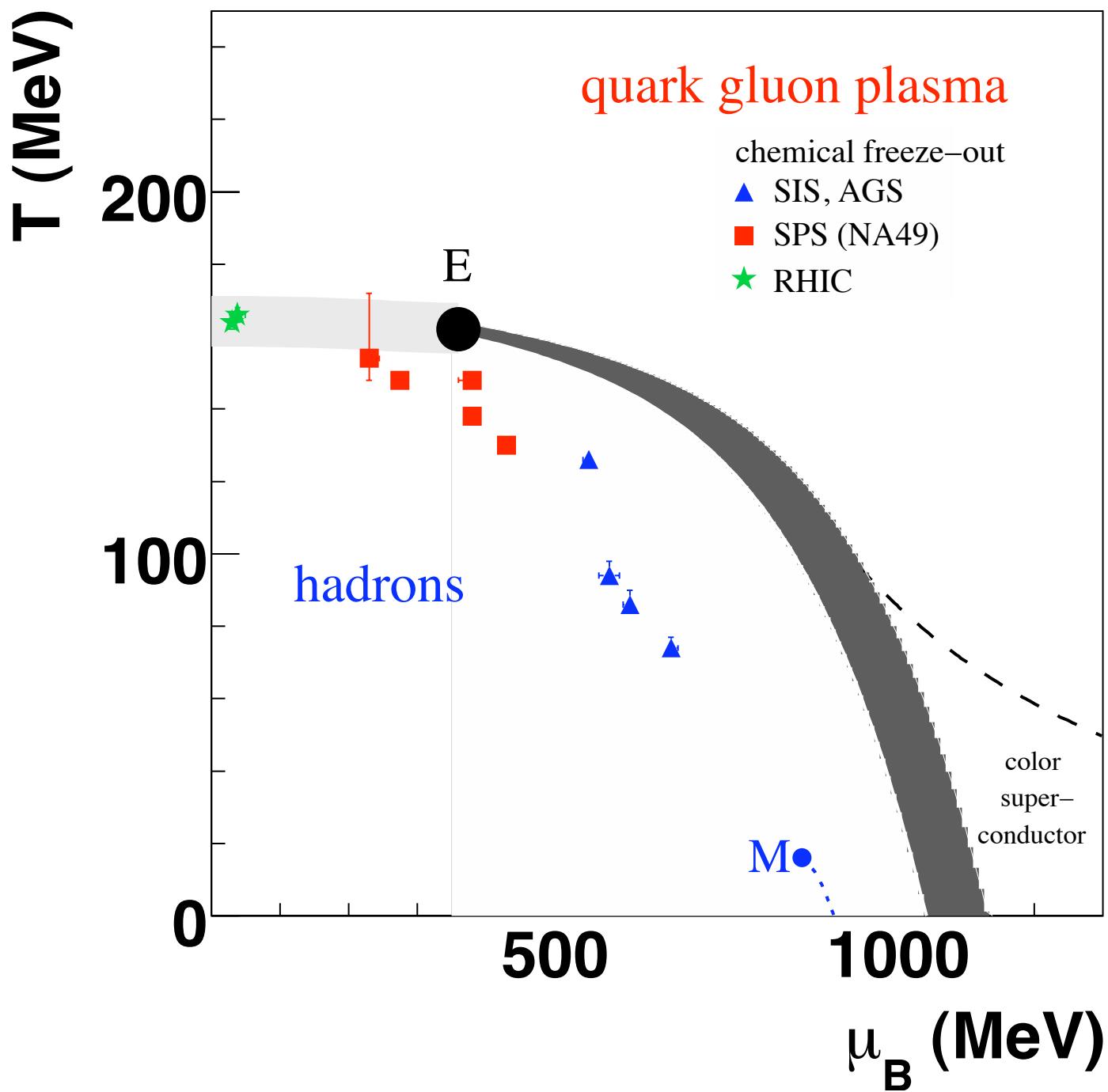




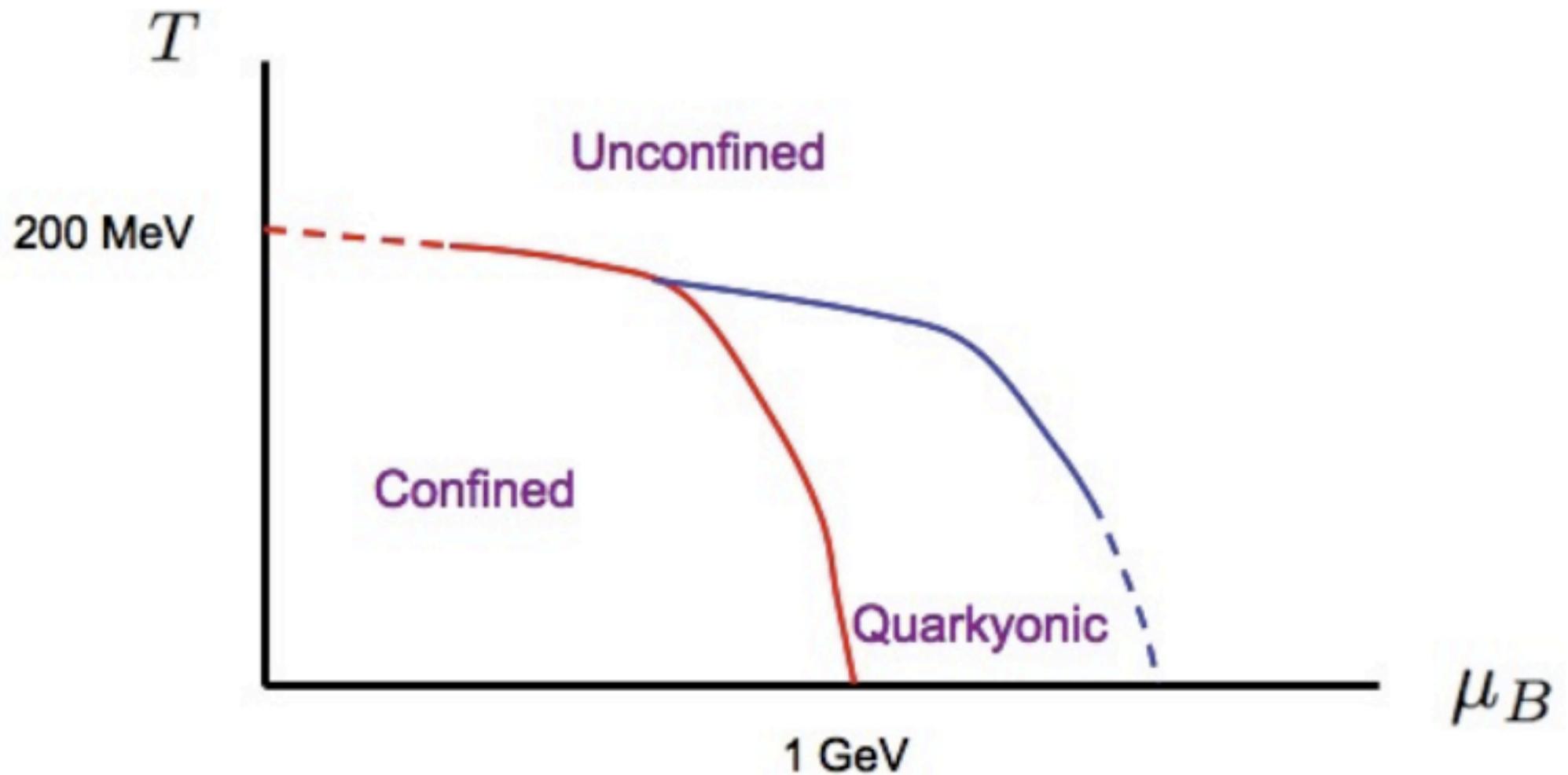
A. Andronic, P. Braun-Munzinger, J. Stachel  
0812.1186 [nucl-th]



## 2.2) Hadro-chemical freeze-out at high $\mu_B$



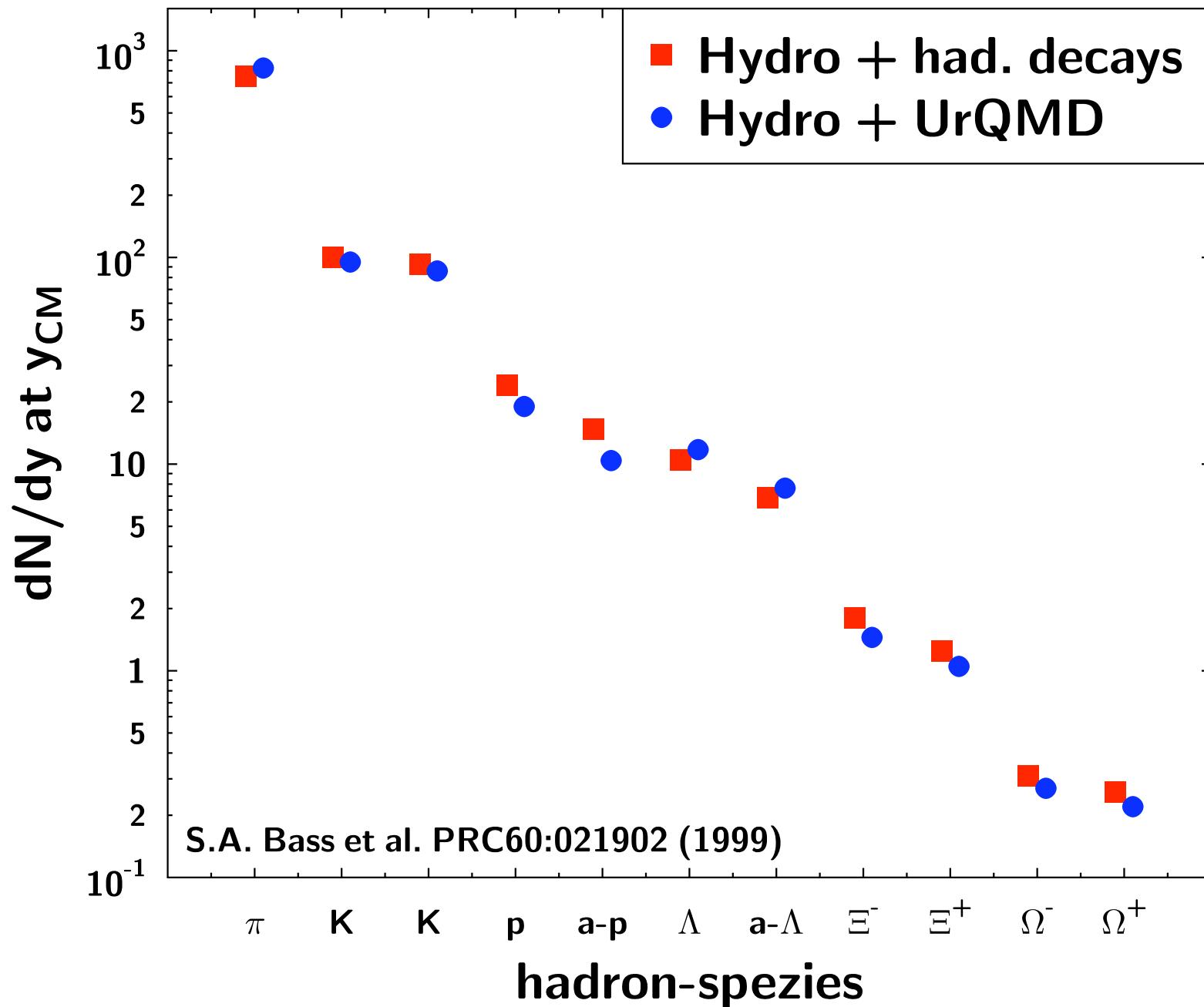
# L. Mc Lerran - Quarkyonic phase



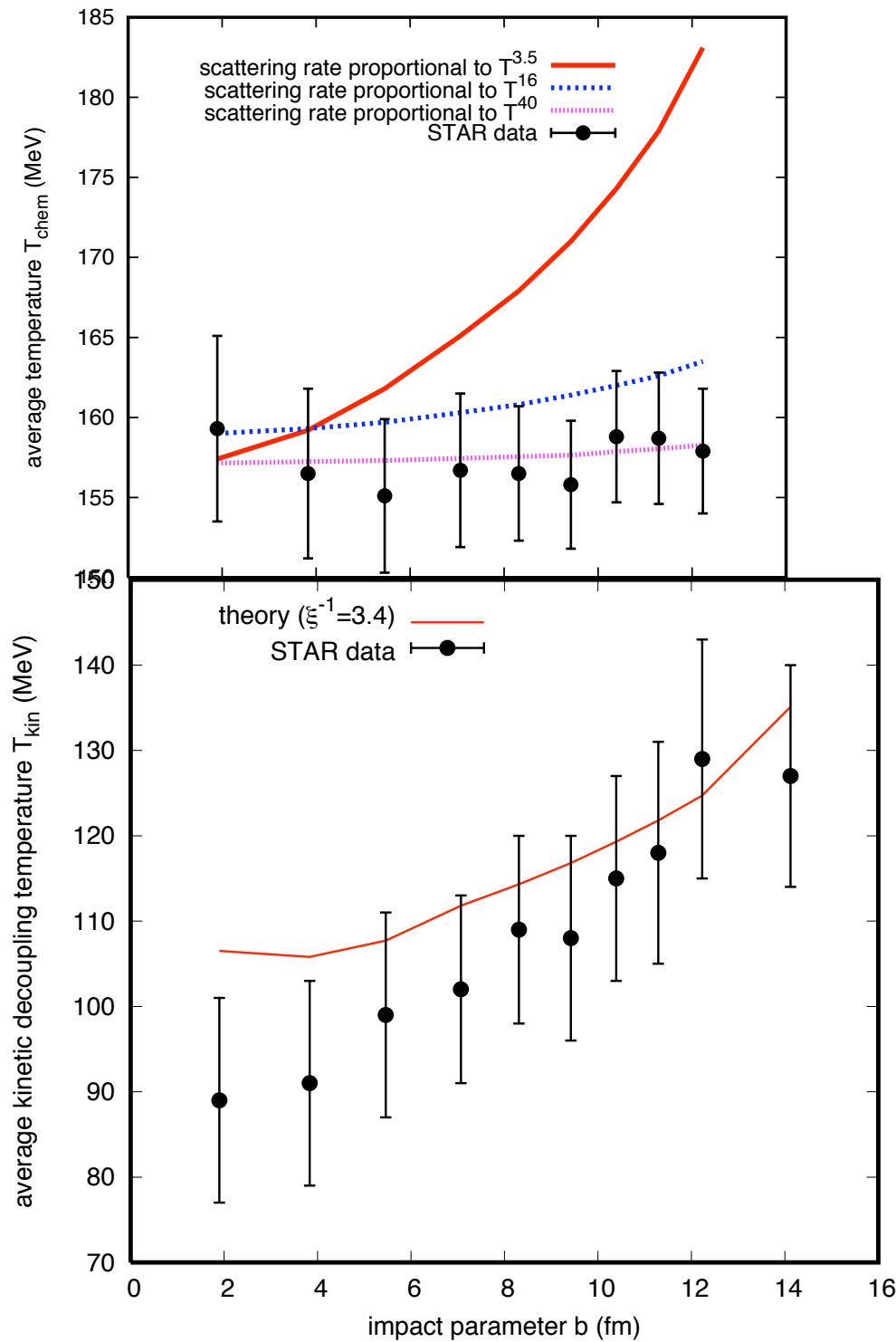
# Hadro-chemical freeze-out at high $\mu_B$

- Sequential freeze-out: Hydro Cooper-Frye decoupling from an expanding hadron resonance gas
- Decay of a strong chiral restoration mean field
- Quarkonium decay à la L. Mc Lerran

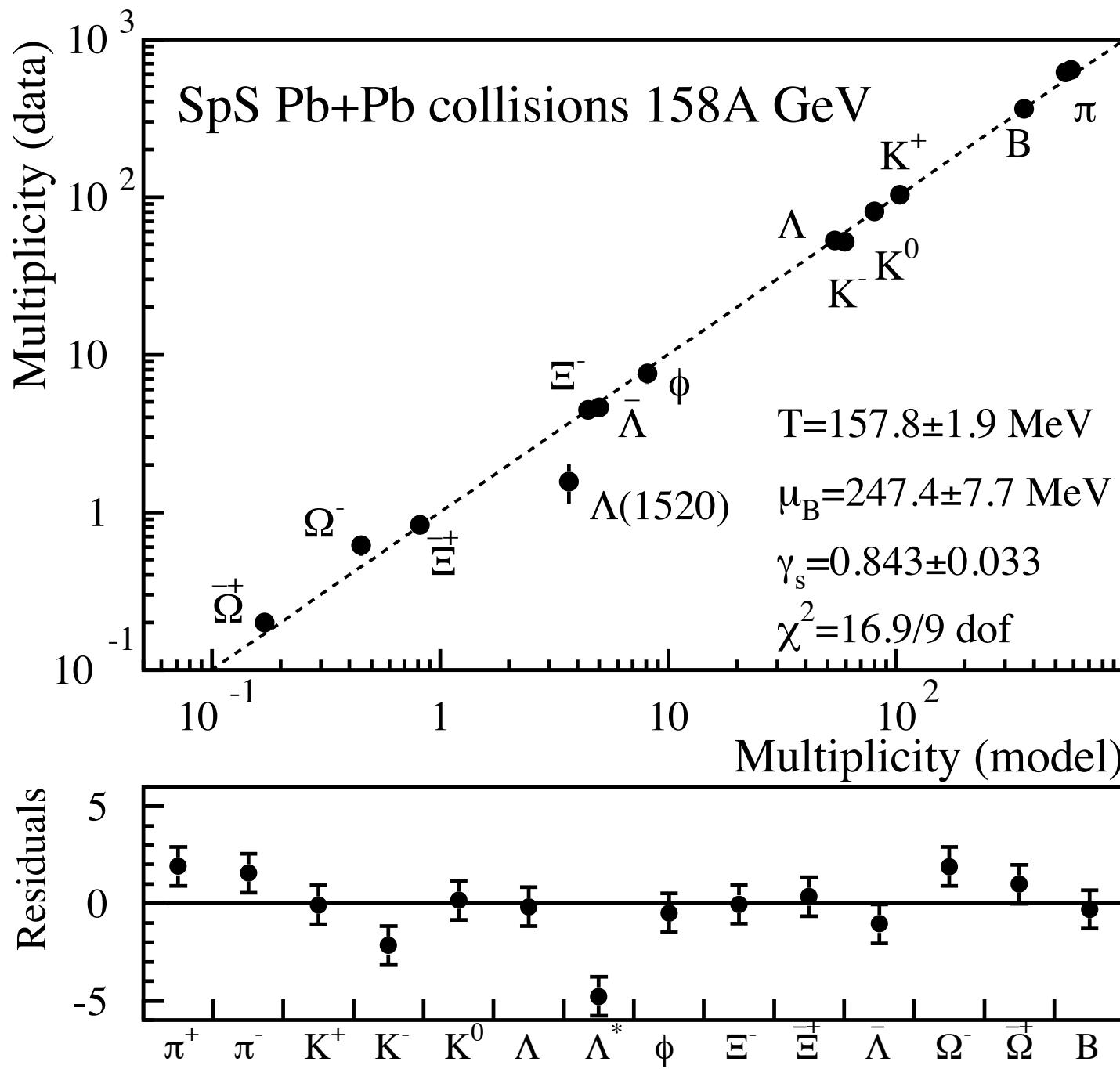
# Au+Au at RHIC

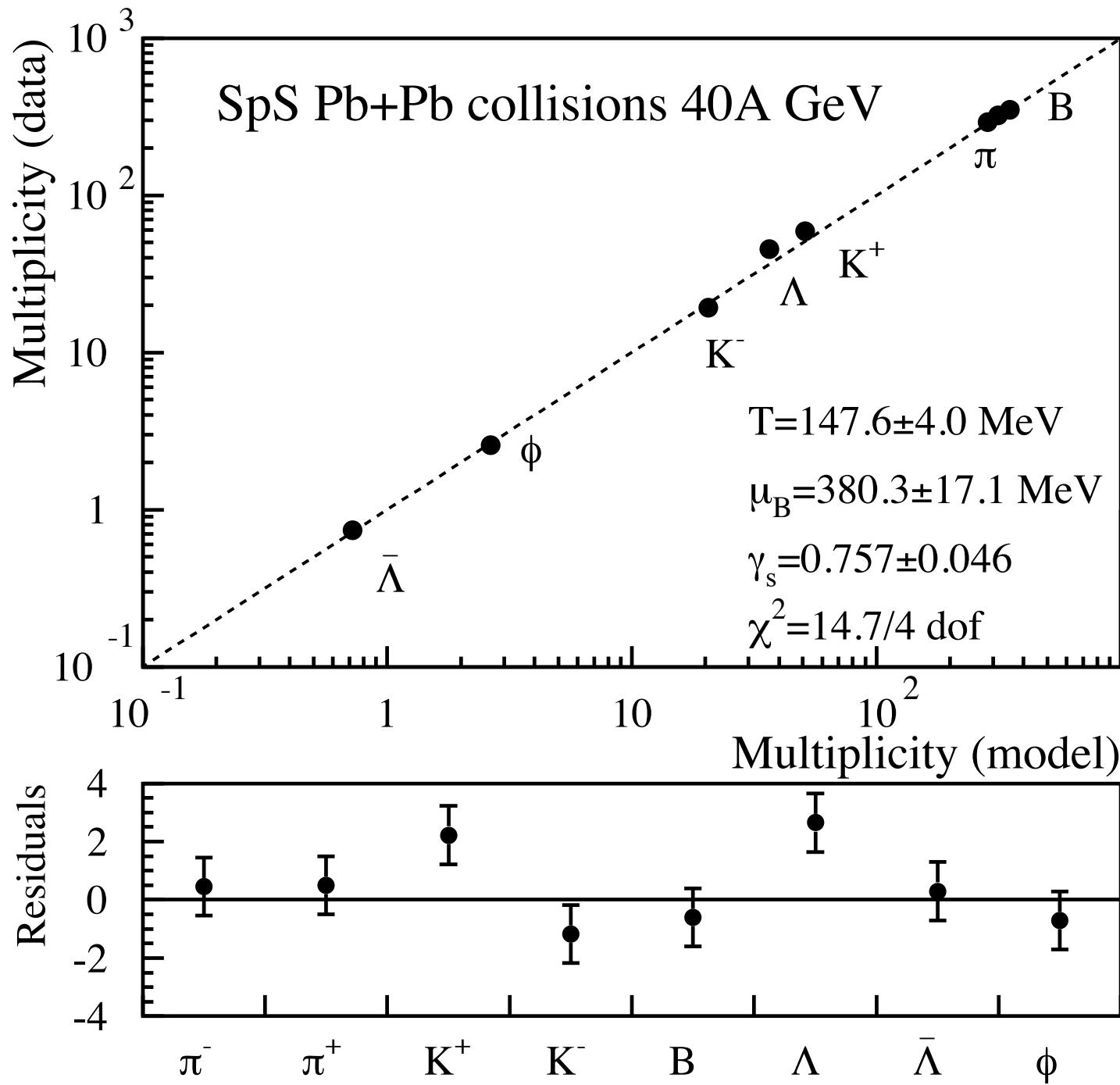


average chemical decoupling temperature vs. impact parameter

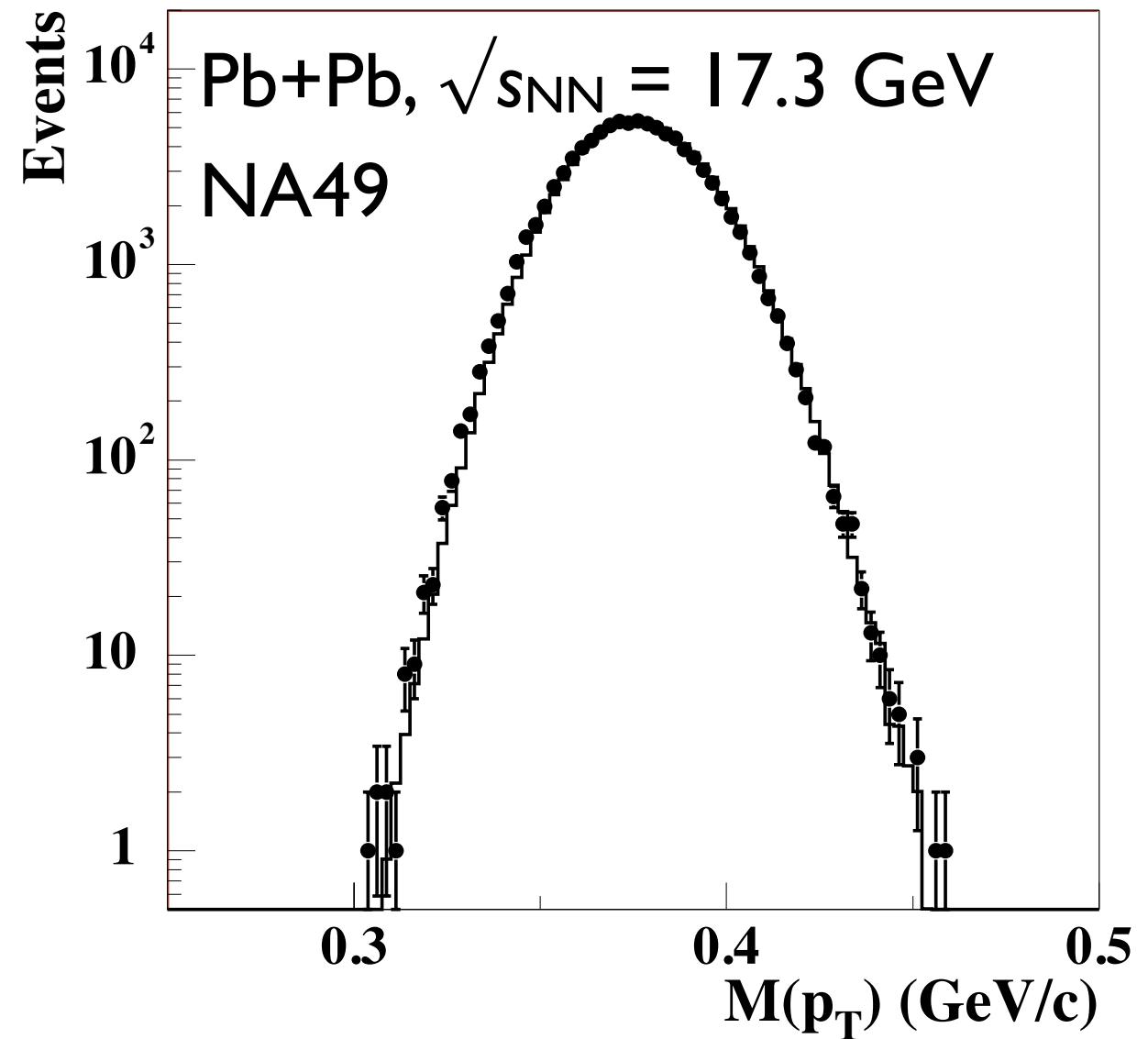


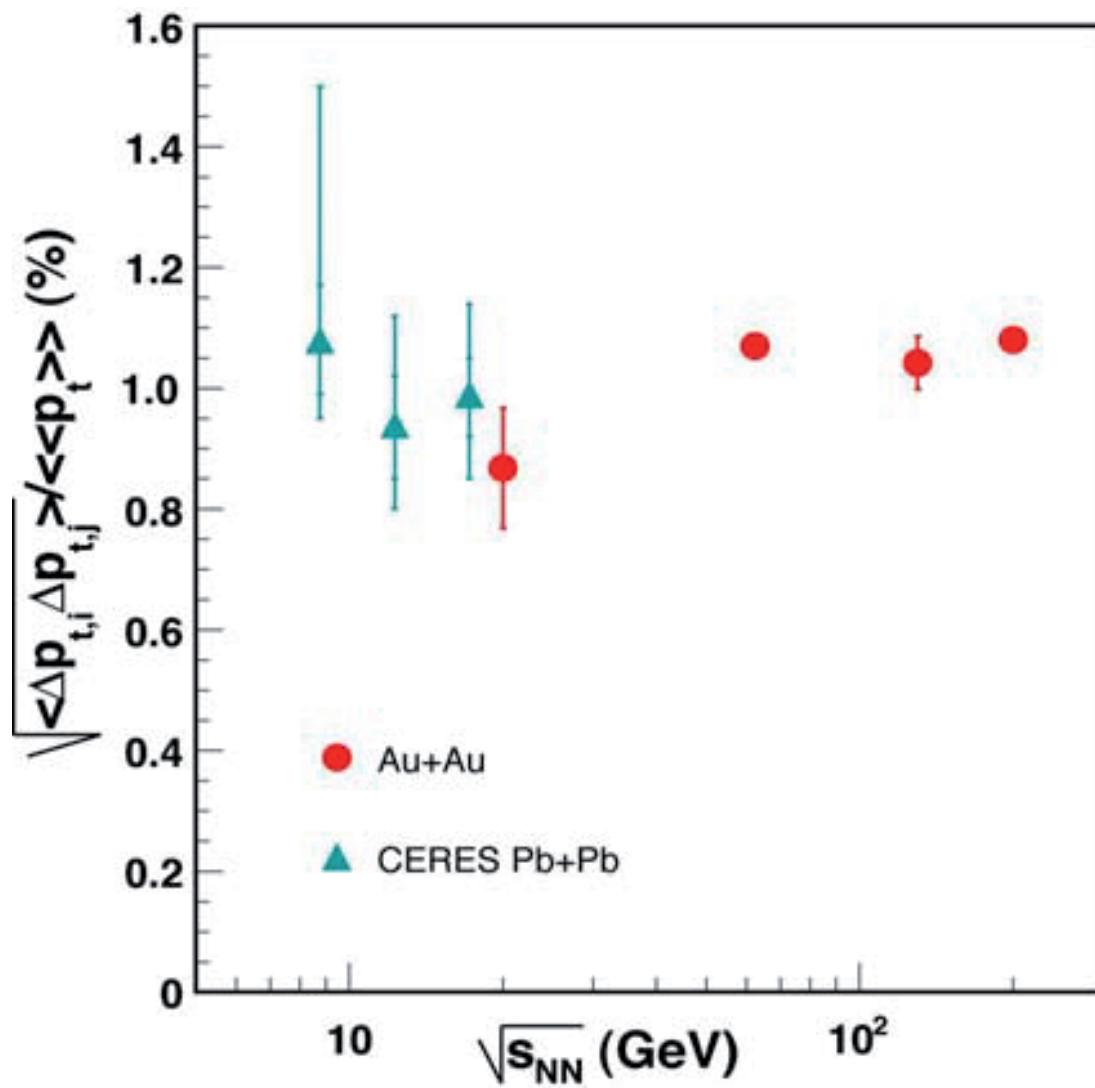
U. Heinz, CPOD Florence



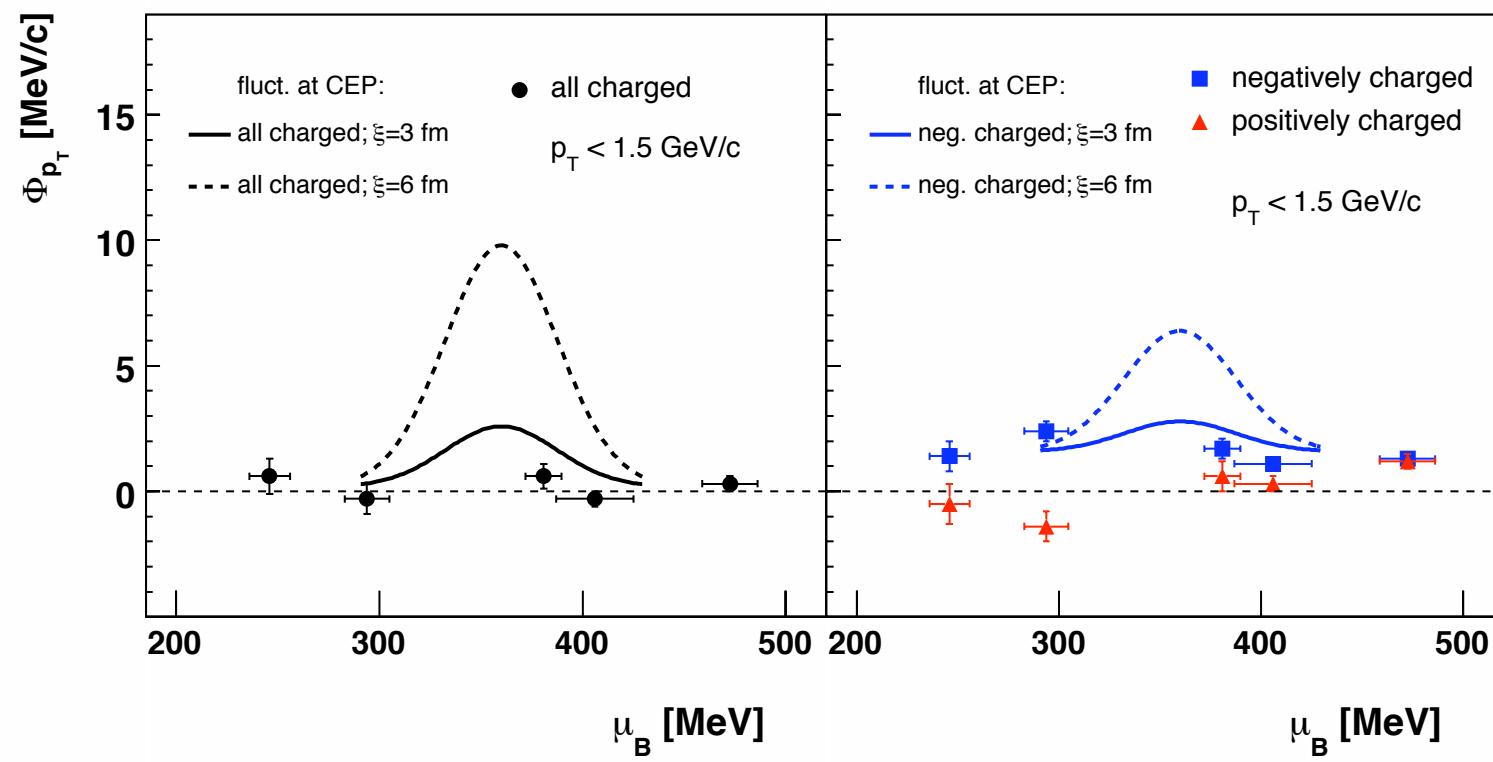


## 2.3 Fluctuation Signals Event-by-event Physics





# Critical Point Effect on $\langle p_T \rangle$ Fluctuations



NA49 data:  
Phys. Rev. C79: 044904, 2009

$\mu_B$  from hadron gas fit:  
F. Becattini et al,  
Phys. Rev. C73: 044905, 2006

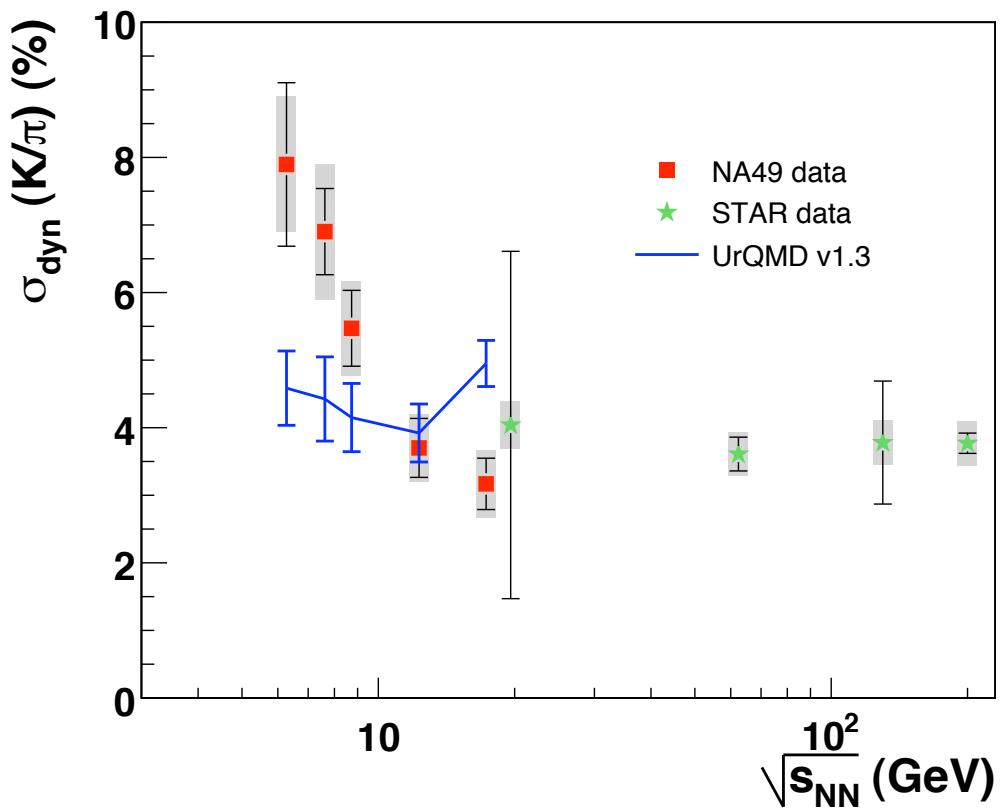
Amplitude of effect:  
Stephanov, Rajagopal, Shuryak,  
Phys. Rev. D60: 114028, 1999  
and private communication

Position of critical point:  
Z. Fodor and S. Katz,  
JHEP 0404, 050, 2004

Width of critical point:  
Y. Hatta and T. Ikeda,  
Phys. Rev. D67: 014028, 2003

Robustness of signal vs. hadronic cascade expansion?

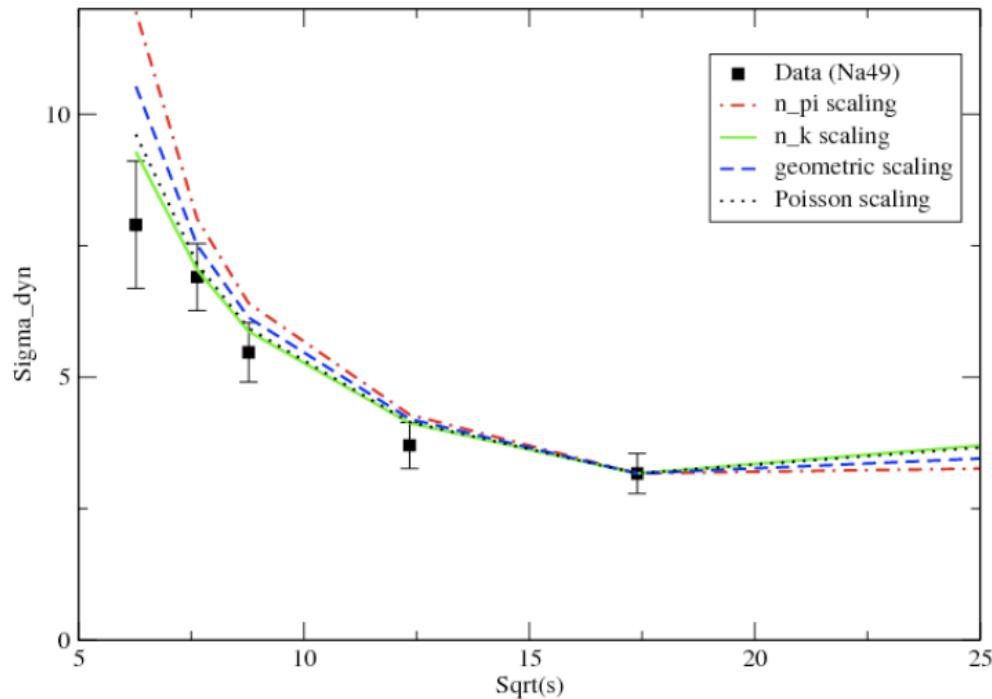
# K/ $\pi$ Ratio Fluctuations



# $K/\pi$ Ratio Fluctuations

V. Koch idea:

$\sigma_{\text{dyn}}$  scales with  $1/(\text{accepted kaon number})$

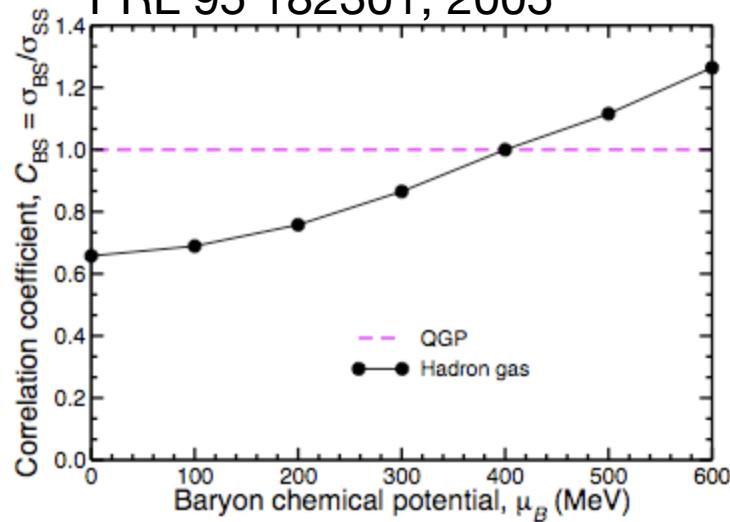


V. Koch: EMMI workshop 2009, Münster (and next talk)

Contradicting interpretations -  
 $K/\pi$  fluctuations remain interesting

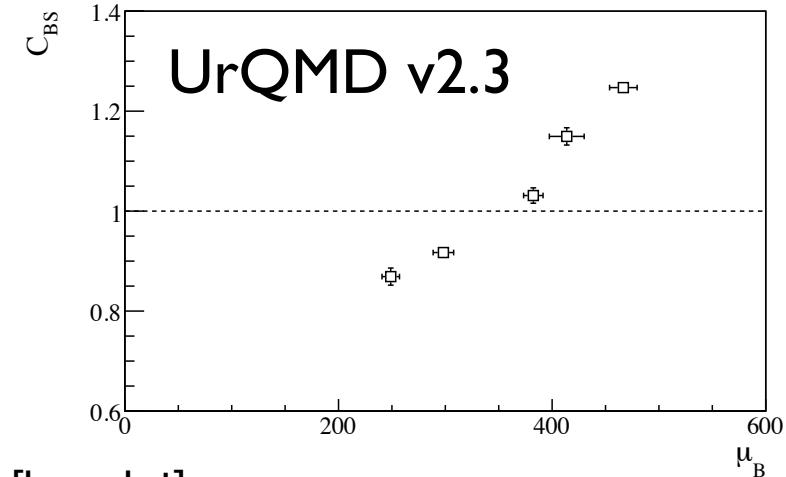
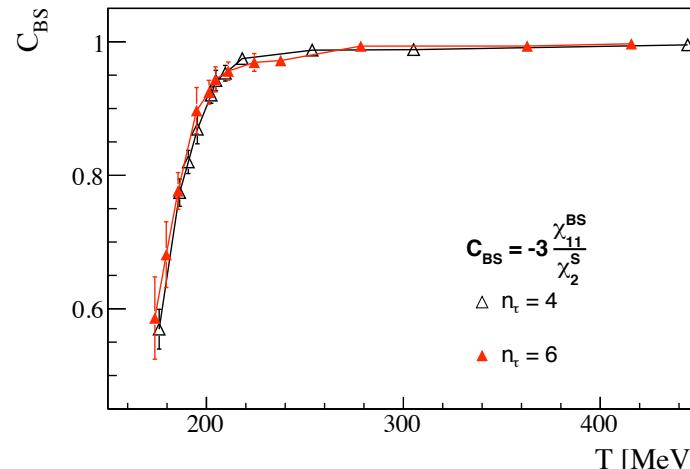
# K/p Ratio Fluctuations

Koch, Majumder, Randrup  
PRL 95 182301, 2005



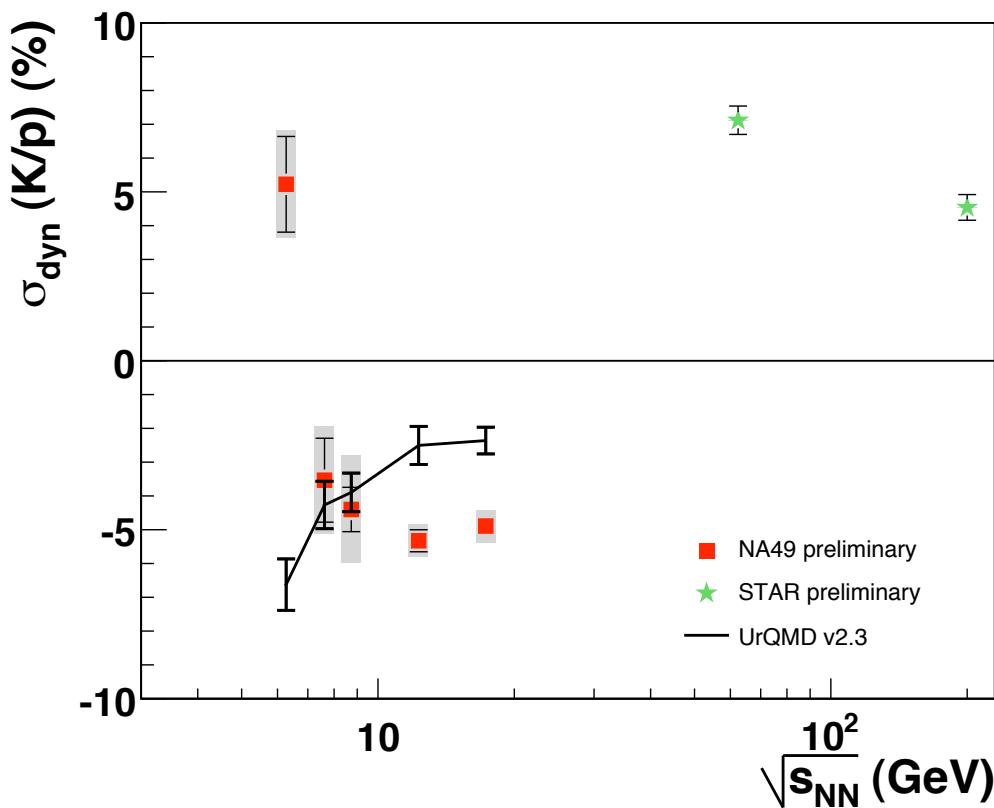
$$C_{BS} = -3 \frac{\langle BS \rangle - \langle B \rangle \langle S \rangle}{\langle S^2 \rangle - \langle S \rangle^2}$$

$$= -3 \frac{\chi_{11}^{BS}}{\chi_2^S}$$



# K/p Ratio Fluctuations

- Two changes of sign visible in the K/p ratio fluctuations
- No obvious scaling behavior visible in the excitation function  
(neither in centrality dependence from STAR, see G. Westfall's talk)

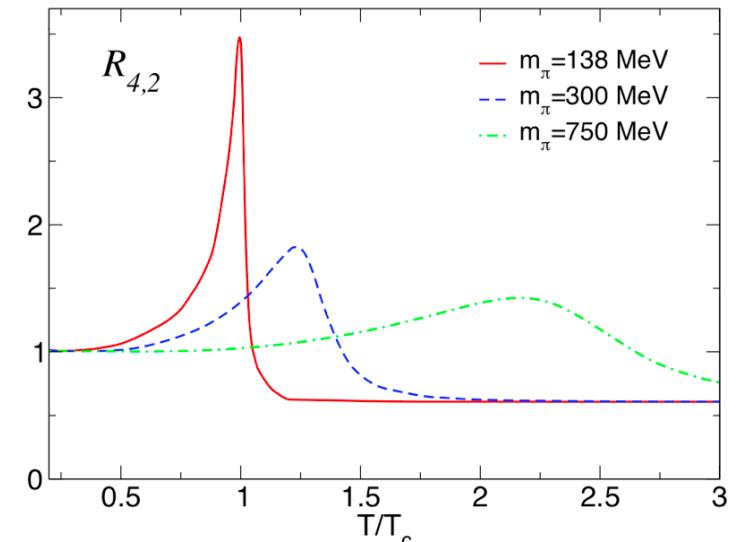


# 3) Outlook

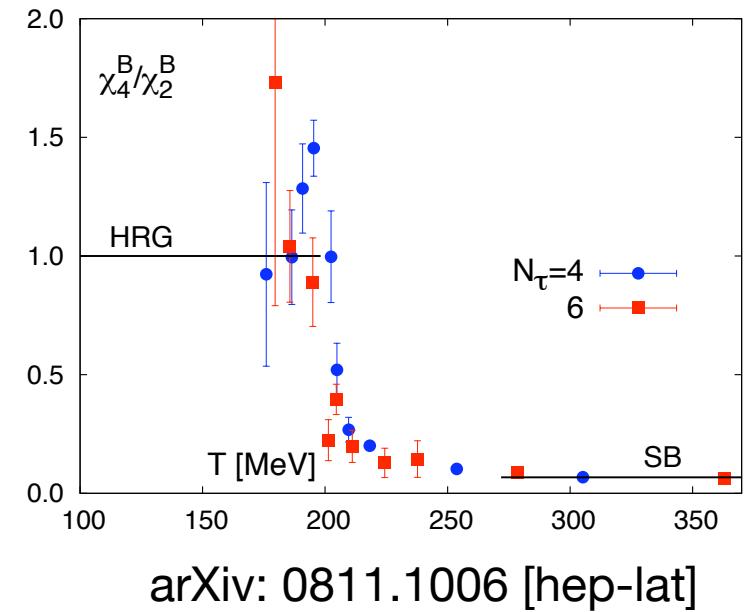
- RHIC Beam Energy Scan
- Fluctuations: Higher moments
- Finite  $\mu_B$  in lattice QCD

# Kurtosis

- Critical point effect
  - Higher moments are more sensitive to diverging sigma field  
Stephanov: PRL 102, 032301 (2009)
  - Reflected in net baryon and net proton kurtosis
  - Divergence of kurtosis confirmed in chiral model
- Phase transition effect
  - In net baryon kurtosis
  - Seen by lattice QCD at  $\mu_B=0$
  - Should be reflected in net protons



arXiv: 0809.3129 [hep-ph]



arXiv: 0811.1006 [hep-lat]

**Thank You!**